

Primordial black holes and the observed Galactic 511 keV line

Cosimo Bambi¹, Alexander D. Dolgov^{2,3,4}, and Alexey A. Petrov^{1,5}

¹*Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA*

²*Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, I-44100 Ferrara, Italy*

³*Dipartimento di Fisica, Università degli Studi di Ferrara, I-44100 Ferrara, Italy*

⁴*Institute of Theoretical and Experimental Physics, 113259 Moscow, Russia*

⁵*Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109, USA*

(Dated: October 17, 2009)

The observed 511 keV line from the Galactic Bulge is a real challenge for theoretical astrophysics: despite a lot of suggested mechanisms, there is still no convincing explanation and the origin of the annihilated positrons remains unknown. Here we discuss the possibility that a population of slowly evaporating primordial black holes with the mass around $10^{16} - 10^{17}$ g ejects (among other particles) low-energy positrons into the Galaxy. In addition to positrons, we have also calculated the spectrum and number density of photons and neutrinos produced by such black holes and found that the photons are potentially observable in the near future, while the neutrino flux is too weak and below the terrestrial and extra-terrestrial backgrounds. Depending on their mass distribution, such black holes could make a small fraction or the whole cosmological dark matter.

INTRODUCTION — It is now clear that in the central region of the Galaxy electron-positron annihilation proceeds at a surprisingly high rate. Confirming precedent measurements [33], the SPI spectrometer on the INTEGRAL satellite has detected an intense 511 keV gamma ray line flux (Bulge component) [3, 4]

$$\Phi_{511 \text{ keV}} = 1.07 \pm 0.03 \cdot 10^{-3} \text{ photons cm}^{-2} \text{ s}^{-1} \quad (1)$$

with a width of about 3 keV, consistent with two dimensional gaussian distribution aligned with the Galactic Center and with a full width at half maximum (FWHM) of about 8° . More recently, the SPI spectrometer has also provided evidence for the disk or halo component [5] of this line.

Non-relativistic positrons in the interstellar medium can either directly annihilate with electrons or form positronium. In the first case they produce two 511 keV photons, while in the second case the annihilation channels are different for para-positronium (formed with 25% probability) and ortho-positronium (formed with 75% probability). Para-positronium decays into two 511 keV γ s, while ortho-positronium decays into three photons with continuous spectrum. From the relative intensities of the 511 keV line and the three γ continuum, one can deduce that the total annihilation rate is 3.6 times larger than the one arising from consideration of flux (1) only [6]. Thus, assuming that the Solar System lies at a distance $r = 8.5$ kpc from the Galactic Center, we can conclude that the total rate is about $3 \cdot 10^{43}$ annihilations per second.

From the theoretical point of view, the issue is to identify the source of these galactic positrons. Many production mechanisms have been suggested, but so far no one is completely satisfactory. Among conventional mechanisms, which do not demand new physics, there are type Ia supernovae [7], low mass X-ray binary systems [3] (see also [8]) and the energetic electrons and photons created by accretion on the super-massive black hole at the Galactic Center [9]. A similar mechanism of

positron production by collision of energetic photons produced in accretion to super-massive central black hole and to surrounding primordial black holes with mass about 10^{17} g was considered in ref. [10]. More exotic scenarios include annihilating light dark matter particles [11], decaying unstable relics and, in particular, sterile neutrinos [12], MeV right-handed neutrino interacting with baryonic matter [13], strangelets [14], positrons originating from primordial antimatter [15], from decays of milli-charged particles [16], and possibly a few more. However, type Ia supernovae have a different galactic distribution and their rate is probably an order of magnitude smaller than the one necessary to explain the observed flux [3, 17] (see however [18]). Low mass X-ray binaries also do not fit the enhanced Bulge component [3]. Lastly, light dark matter particles are theoretically not well motivated, might be inconsistent with observations [19], and their mass should be very close to the electron one, because from the comparison of the Galactic gamma ray emission above and below 511 keV, one can conclude that the injected energy of the positrons cannot be larger than about 3 MeV [6].

In this letter, we discuss the possibility that positrons are produced by evaporating primordial Black Holes (BHs). As in the case of MeV dark matter, some fine tuning is needed too, namely, the BH mass distribution should be peaked in the interval $10^{16} - 10^{17}$ g. The idea that the primary source of low energy positrons in the Galaxy could be primordial BHs was first considered in ref. [20]. The picture was later discussed in ref. [21], with the conclusion that primordial BHs could unlikely be responsible for the 511 keV line from the Galactic Center, unless the primordial BHs are more strongly clustered in the halo than the other halo material. However, the authors of ref. [21] assumed that the initial mass distribution of BHs, dN/dM , is scale invariant, while we have considered a mass distribution which is peaked at a particular value. In this case primordial BHs can account for the observed 511 keV photons and, at the same

time, could make even the whole cosmological dark matter, with no contradiction with the observed gamma ray backgrounds and gravitational lensing data, if the mass spectrum of BHs has a pronounced maximum in the interval $10^{16} - 10^{17}$ g. A mechanism of creation of primordial BH dark matter with a peaked mass distribution was suggested e.g. in ref. [22].

PRIMORDIAL BHS: GENERAL FEATURES — It is well known that at the semiclassical level BHs are no longer one-way membranes, but emit the Hawking radiation [23]. Restricting to the simplest case of a Schwarzschild BH with mass M , the emission rate of the particles of species i with the energy in the range $(E, E + dE)$, orbital momentum l , third component of the orbital momentum m and polarization s is [34]:

$$\frac{dN_{ilms}}{dt} = \frac{\Gamma_{ilms}}{(2\pi)} \frac{dE}{\exp(E/T) \pm 1}, \quad (2)$$

where Γ_{ilms} is the so-called graybody factor equal to the absorption probability for an incoming wave with the specified quantum numbers, T is the Schwarzschild BH temperature

$$T = \frac{1}{8\pi G_N M} = 1.06 \left(\frac{10^{16} \text{ g}}{M} \right) \text{ MeV} \quad (3)$$

and the signs \pm are for fermions and bosons respectively. At high energies ($G_N M E \gg 1$), $\sum \Gamma_{ilms} \propto (ME)^2$, since the cross section for each kind of particle approaches the geometrical-optics limit, and BH radiates basically as black body of the same temperature.

As one can easily see from eq. (3), the temperature of an astrophysical BH with the mass of the order of the Solar mass $M_\odot \approx 2 \cdot 10^{33}$ g, or larger, is very low, below 10^{-7} K, and the corresponding particle emission is completely negligible. However, lighter BHs could have been produced in the very early universe by a lot of possible mechanisms (for a review of production mechanisms and observational bounds see e.g. [24] and references therein) and today evaporate at a much higher temperatures. From eq. (2), one can compute the total particle emission rate and the total BH mass loss rate [25, 26]

$$\begin{aligned} \frac{dN}{dt} &= \sum_{ilms} \int \frac{\Gamma_{ilms}}{\exp(E/T) \pm 1} \frac{dE}{(2\pi)} = \frac{\alpha'}{G_N M} = \\ &= 1.1 \cdot 10^{20} \left(\frac{\alpha'}{2.6 \cdot 10^{-3}} \right) \left(\frac{10^{16} \text{ g}}{M} \right) \text{ s}^{-1}, \quad (4) \\ \frac{dM}{dt} &= - \sum_{ilms} \int \frac{\Gamma_{ilms}}{\exp(E/T) \pm 1} \frac{E dE}{(2\pi)} = - \frac{\alpha}{G_N^2 M^2} = \\ &= -4.8 \cdot 10^{20} \left(\frac{\alpha}{4.5 \cdot 10^{-4}} \right) \left(\frac{10^{16} \text{ g}}{M} \right)^2 \text{ MeV s}^{-1}, \quad (5) \end{aligned}$$

where α' and α are numerical coefficients depending on the BH mass M and the particle content of the theory. In the Standard Model, for $M \gg 10^{17}$ g, one finds $\alpha' =$

$1.6 \cdot 10^{-3}$ and $\alpha = 2.8 \cdot 10^{-4}$, while, for $5 \cdot 10^{14} \text{ g} \ll M \ll 10^{17} \text{ g}$, $\alpha' = 2.6 \cdot 10^{-3}$ and $\alpha = 4.5 \cdot 10^{-4}$ [35]. From eq. (5), we can find the BH lifetime

$$\begin{aligned} \tau_{\text{evap}} &= \frac{G_N^2 M_i^3}{3\alpha_i} = \\ &= 15 \left(\frac{4.5 \cdot 10^{-4}}{\alpha_i} \right) \left(\frac{M_i}{5 \cdot 10^{14} \text{ g}} \right)^3 \text{ Gyr}, \quad (6) \end{aligned}$$

where $\alpha_i = \alpha(M_i)$ and M_i is the initial BH mass, since the BH spends most of its life near its original mass. From eq. (6) we see that all the primordial BHs with the original mass lighter than $5 \cdot 10^{14}$ g have already evaporated.

PRIMORDIAL BHS IN OUR GALAXY — Let us start with a first estimate, just to show that primordial evaporating BHs can be viable candidates to explain the observed 511 keV line from the Galactic Bulge. For this purpose, we assume that all the BHs have the same mass $M = 6 \cdot 10^{16}$ g. The positron production rate per BH is

$$\frac{dN_{e^+}}{dt} \approx 0.7 \frac{\alpha'_{e^+}}{G_N M} \approx 2 \cdot 10^{18} \text{ e}^+ \text{ s}^{-1}, \quad (7)$$

where $\alpha'_{e^+} = 0.49 \cdot 10^{-3}$ and the factor 0.7 is the correction due to the finite value of the positron mass. In order to explain the observational data, which suggest that the positron production rate is $3 \cdot 10^{43} \text{ e}^+ \text{ s}^{-1}$ inside a spherical region of the radius $r = 500 - 700$ pc, we need about $1.5 \cdot 10^{25}$ primordial BHs, whose total mass is $\sim 4.5 \cdot 10^8 M_\odot$. Here positrons are injected into the Galaxy non-relativistically, together with electrons, photons and neutrinos (and possible other unknown light particles).

The neutrino flux on the Earth would be extremely weak, about $0.02 \nu \text{ cm}^{-2} \text{ s}^{-1}$, impossible to be detected by present and foreseeable future experiments.

The photon flux from the Galactic Center would be about an order of magnitude less intense than that of

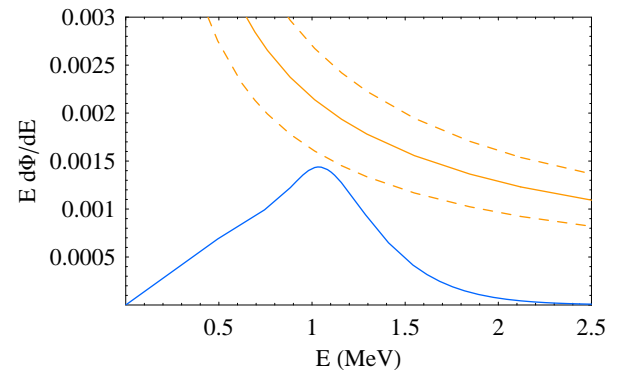


FIG. 1: Gamma ray spectra from primordial BHs with mass $M = 6 \cdot 10^{16}$ g (blue solid curve) and of the diffuse background (red dashed curve) in $\gamma \text{ cm}^{-2} \text{ s}^{-1}$ as a function of energy E in MeV. The number of BHs is normalized by the condition that they produce the observed positron flux.

neutrinos [36], i.e.

$$\Phi_{\gamma, \text{BH}} \approx 1.8 \cdot 10^{-3} \gamma \text{ cm}^{-2} \text{ s}^{-1}, \quad (8)$$

and may be observable as a possible bump in the diffuse background of the Galactic Center. The presence of the bump depends on the exact position of the peak in the photon spectrum from evaporating BHs. The correct BH photon cross section depends also on the energy of the emitted photon, that is $\sigma_\gamma = \sigma_\gamma(M, E)$, and has to be computed numerically [25, 26]. In this paper we use the photon cross section that one can deduce by fitting the curve reported in Fig. 1 of ref. [26]. The gamma spectrum from primordial BHs is plotted in Fig. 1 together with the measured Galactic continuum one [4, 27]

$$\frac{d\Phi_{\text{cont}}}{dE} = A \left(\frac{E}{0.511 \text{ MeV}} \right)^{-1.75}, \quad (9)$$

where $A = 7 \cdot 10^{-3} \gamma \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$ is the normalization factor at $E = 0.511 \text{ MeV}$.

We can also notice that the cosmological dark matter may be made of $6 \cdot 10^{16} \text{ g}$ primordial BHs: their number density today would be $n_{\text{BH}} = 4 \cdot 10^{-47} \text{ cm}^{-3}$ and they would have created a cosmological MeV gamma background $n_\gamma \approx 1.1 \cdot 10^{-11} \text{ cm}^{-3}$ or, equivalently, an isotropic flux $\Phi_\gamma \approx 0.3 \gamma \text{ cm}^{-2} \text{ s}^{-1}$. The latter is about what we observe, so it is not unreasonable that the Dark Matter (DM) in the Universe is made of BHs with mass $M = 6 \cdot 10^{16} \text{ g}$.

If the mass fraction of BH with $M = 6 \cdot 10^{16} \text{ g}$ with respect to the total amount of DM in the Galactic Center is the same as the cosmological average, we would expect about $10^{10} M_\odot$ of DM in the Galactic Bulge. As we see later this is a reasonable result. On the other hand, we can avoid this restriction if the bulk of DM are not BHs but is of some other form, e.g. massive stable elementary particles. In this case the fraction of BHs in the Bulge can be larger than the cosmological average and the amount of DM in the Bulge may be significantly smaller than $10^{10} M_\odot$.

Keeping an open mind to this possibility, we will concentrate on a more economical case that all cosmological DM consists of primordial BHs, considering a more realistic mass distribution than a delta function. The mass distribution of such BHs is model dependent and in particular strongly depends upon the BH production mechanism in the early Universe. One possibility is the model suggested in ref. [22], where in the simplest case the BH mass distribution has the log-normal form [37]

$$\frac{dN}{dM} = C \exp \left(-\gamma \ln^2 \frac{M}{M_0} \right), \quad (10)$$

where C , γ and M_0 are unknown parameters of the underlying theory. Let us note that this distribution is rather sharply peaked near mass M_0 for $\gamma \geq 1$. Strictly speaking the distribution given by eq. (10) is the initial mass distribution, and the primordial BH masses

changed in the course of cosmological evolution. There are two possible effects: evaporation which leads to mass loss and accretion which results in the mass increase. The latter leads to mass rise proportional to the square of the initial mass and weakly change the distribution. The evaporation results in complete destruction of primordial BHs with small initial masses, $M \leq 5 \cdot 10^{14} \text{ g}$, and thus to decrease the spectrum at small masses. For the taken here mass distribution with $M_0 \sim 6 \cdot 10^{16} \text{ g}$ and $\gamma \geq 1$ the present mass distribution is quite close to the primordial one, because the mass fraction of BHs which have already evaporated is small (see below for more details).

The total amount of DM in the Galactic Center is poorly known. The observed rotation curve requires that the total mass in the Galactic Bulge is roughly $10^{10} M_\odot$ and though this can be explained by the known baryonic components, see e.g. ref. [28], it is natural to expect that the amount of DM is of the same order of magnitude as that of baryons. N-body simulations predict some cusp of DM in the center of galaxies [29], since the typical DM density profile is $\rho \sim r^{-\beta}$ with $\beta = 0 - 2$. In conclusion, $\sim 10^{10} M_\odot$ is a reasonable upper bound on the amount of DM in the region where most positrons annihilate. So, if we assume for example that the total mass in the form of primordial BHs in this region is $5 \cdot 10^9 M_\odot$, we find that the choice $\gamma = 1$ and $M_0 = 6 \cdot 10^{16} \text{ g}$ can explain the 511 keV line flux from the Galactic Center and be consistent with the observed galactic and extra-galactic gamma backgrounds. This can be seen as follows. By integrating over all the masses, we find the normalization constant C

$$\int \frac{dN}{dM} dM \Big|_{\gamma=1, M_0=6 \cdot 10^{16} \text{ g}} = 5 \cdot 10^9 M_\odot \quad (11)$$

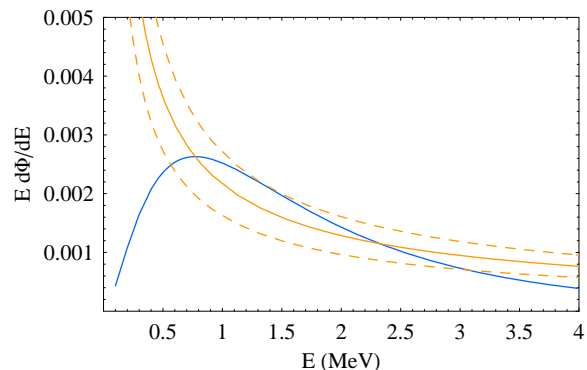


FIG. 2: Gamma ray spectra from primordial BHs (dark-blue solid curve) and of the measured background (light-red solid curve) from the Galactic Bulge in $\gamma \text{ cm}^{-2} \text{ s}^{-1}$ as a function of energy E in MeV. The BHs are assumed to have log-normal mass distribution, eq. (10), with the parameters: $\gamma = 1$ and $M_0 = 6 \cdot 10^{16} \text{ g}$. The number of BHs is now normalized by the condition that their total mass in the innermost 0.6 kpc is $5 \cdot 10^9 M_\odot$. The gamma flux from primordial BHs does not exceed the $\pm 25\%$ uncertainty of the measured gamma ray flux (red dashed lines) and can produce enough positrons to explain the 511 keV line.

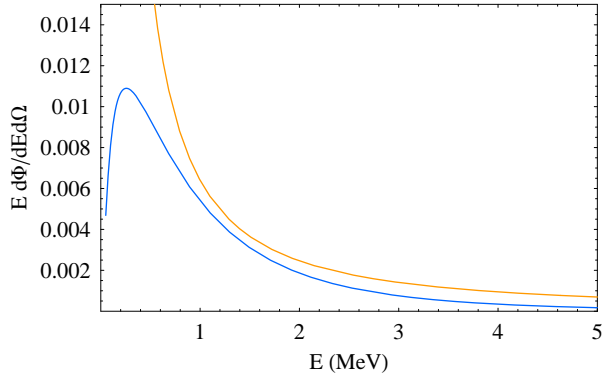


FIG. 3: Cosmic isotropic gamma ray spectra from primordial BHs (dark-blue curve) and of the measured background (light-red curve) in $\gamma \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ as a function of energy E in MeV. Here we assume that the BHs make the whole cosmological dark matter and have log-normal mass distribution, eq. (10), with the parameters: $\gamma = 1$ and $M_0 = 6 \cdot 10^{16} \text{ g}$.

and then we can obtain the photon flux arriving on the Earth

$$\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi r^2} \int \frac{dN_\gamma}{dE dt} \frac{dN}{dM} dM. \quad (12)$$

Here we can use the initial mass distribution, eq. (10), and integrate out from 0 to infinity because the corrections due to BH evaporation are negligible. $dN_\gamma/dEdt$ is provided by eq. (4). Fig. 2 shows the gamma spectra from the Galactic Bulge produced by the primordial BHs (dark-blue solid curve) and the observed gamma background of eq. (9) (red solid curve). The $\pm 25\%$ uncertainty of the gamma background (light-red dashed curves) is at least a reasonable estimate of the 2σ curve, see refs. [4, 27].

The isotropic cosmological gamma background produced by primordial BHs in the whole history of the Universe depends only on the parameter γ and M_0 , if the normalization constant C is found from the requirement that the primordial BHs make the whole cosmological DM, whose energy density is known to be

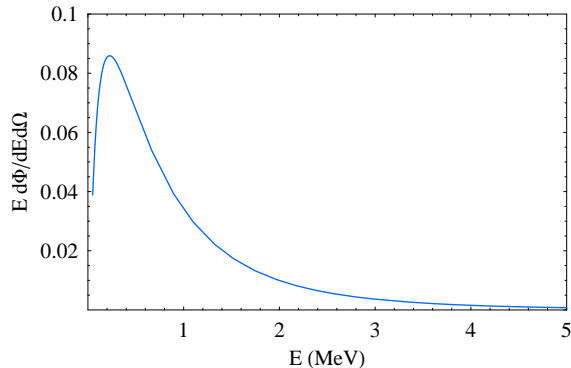


FIG. 4: Diffuse cosmic neutrino spectrum from primordial BHs in $\nu \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ as a function of energy E in MeV. The assumptions are the same as of Fig. 3.

$\rho_{DM} \approx 2.4 \cdot 10^{-30} \text{ g cm}^{-3}$. The estimate of the diffuse photon flux is (see e.g. ref. [30] for the derivation of the formula)

$$\frac{d\Phi_{\text{cosmic}}}{dE} = \frac{1}{4\pi} \int \frac{dn}{dM}(M) \frac{dN_\gamma}{dt dE'}(M, E(1+z)) \frac{dz}{H_0 h(z)} \quad (13)$$

where dn/dM is the comoving number density of primordial BHs with mass M , $h(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$ and H_0 the Hubble parameter today. The spectrum is presented in Fig. 3, together with the measured extragalactic continuum [31]

$$\frac{d\Phi_{\text{extra}}}{dE} = B \left(\frac{E}{1 \text{ MeV}} \right)^{-2.38}, \quad (14)$$

where $B = 6.4 \cdot 10^{-3} \gamma \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}$ is the normalization factor. Eq. (14) fits quite well the observed spectrum in the energy range $0.1 - 10 \text{ MeV}$. Contrary to the simplest case of primordial BHs with equal masses, i.e. with the delta-function spectrum, primordial BHs with sufficiently wide spectrum may explain the observed annihilation line, be in agreement with the observed gamma background, and make all cosmological DM.

Fig. 4 shows the expected cosmological neutrino background from the evaporating primordial BHs. Unfortunately, such neutrinos are difficult to observe, because they are below the solar and terrestrial neutrino fluxes.

One could also wonder about the impact of the primordial BH positron and electron emission spectra on the diffuse Galactic backgrounds. Simple considerations suggest that MeV positrons and electrons produced in the Galactic Bulge are confined to the Galactic Bulge [11] and therefore their flux on the Earth is negligible. Even if we take into account the fact that such primordial BHs could make the whole cosmological DM, and thus some of them are also in the neighborhood of the Solar System, one cannot expect any effect on the measured Galactic background, because most of the positrons are non-relativistic and are likely unable to reach a detector which is located on a satellite orbiting around the Earth.

The positrons produced by primordial BHs have low energies and there is no contradiction with the bound deduced in ref. [6]. Actually, the constraint of 3 MeV is obtained assuming that all the positrons have the same energy, so it is not easy to apply the result to more general cases. However, we can quickly see that in the scenario proposed in this paper the positrons with energies above 3 MeV are about 5% of the total number of positrons produced by Hawking evaporation. This is found calculating the integral

$$\int dM M^2 \frac{dN}{dM} \int_{3 \text{ MeV}}^{\infty} dE \frac{E \sqrt{E^2 - m_e^2}}{1 + \exp(E/T)} \quad (15)$$

and dividing by the same integral evaluated between m_e and infinity. Including the grey-body effect, the correction to this estimate is irrelevant, close to a factor 1.1.

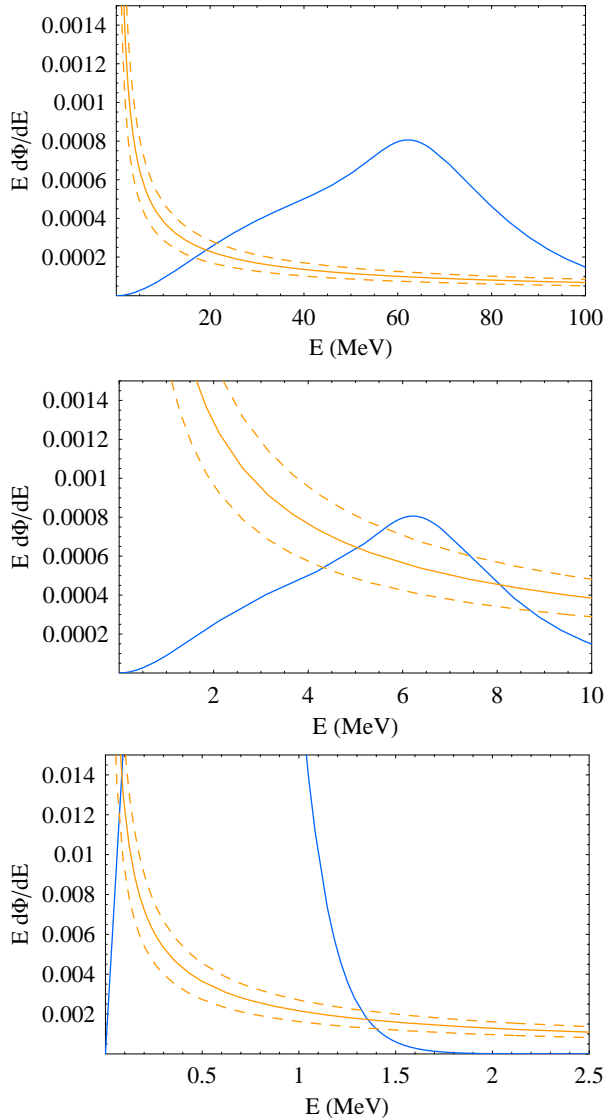


FIG. 5: Gamma ray spectra from primordial BHs (dark-blue solid curve) and of the measured background (light-red solid curve) from the Galactic Bulge in $\gamma \text{ cm}^{-2} \text{ s}^{-1}$ as a function of energy E in MeV. The BHs are assumed to have all the same mass: $M = 10^{15} \text{ g}$ (upper panel), $M = 10^{16} \text{ g}$ (central panel) and $M = 10^{17} \text{ g}$ (lower panel). The number of BHs is normalized by the condition that they produce the right amount of positrons to explain the observed 511 keV line. Red dashed lines are the $\pm 25\%$ uncertainty of the measured diffuse gamma flux.

The mass distribution of eq. (10) includes also very light BHs which have already evaporated. For our choice $\gamma = 1$ and $M_0 = 6 \cdot 10^{16} \text{ g}$, the initial fraction of BHs with masses smaller than $5 \cdot 10^{14} \text{ g}$, and hence lifetimes shorter than the present age of the Universe, is negligible, at the level of 10^{-16} . However, the total amount of matter converted into relativistic particles from the birth of the Universe up to today is much larger: the dominant contribution comes from BHs which still exist

in the Universe and are basically evaporating at a constant rate, because the process is slow and their mass is still very close to the initial one. Assuming that primordial BHs make the all DM, today the cosmic energy density of the particles produced by BH evaporation is roughly $10^{-7} \rho_{DM}$. The photon flux is the one reported in Fig. 3.

Lastly, we would like to note that the BH masses are strongly constrained by the gamma ray continuum from the Galactic Center. Indeed, neglecting any possible correlation between primordial BHs and DM, we can consider three simple cases, where all the BHs have the same mass: $M = 10^{15} \text{ g}$, $M = 10^{16} \text{ g}$ and $M = 10^{17} \text{ g}$. In order to explain the observed 511 keV gamma flux, the total mass of primordial BHs in the Galactic Bulge should respectively be about $7 \cdot 10^4 M_\odot$, $7 \cdot 10^6 M_\odot$ and $9 \cdot 10^{10} M_\odot$. The produced galactic photon background for these cases is presented in Fig. 5. For low BH masses, the BH temperature is high and too many high energy photons are produced. For high masses, the positron emission is exponentially suppressed by the Boltzman factor and to explain the observed 511 keV line we would need a large number of BHs, with the effect that the low energy gamma spectrum is too intense. Hence, we can conclude that, assuming that the positron flux is produced by primordial BHs, the BH mass distribution has to be peaked around 10^6 g and actually rather sharply peaked near $6 \cdot 10^{16} \text{ g}$.

CONCLUSION — We have considered evaporating primordial BHs, as a possible source of positrons to generate the observed photon 511 keV line from the Galactic Bulge. The analysis of the accompanying continuous photon background produced, in particular, by the same evaporating BHs, allows to fix the mass of the evaporating BHs near 10^{16} g . It is interesting that the necessary amount of BHs could be of the same order of magnitude as the amount of dark matter in the Galactic Bulge. This opens a possibility that such primordial BHs may form all cosmological dark matter. The background MeV photons created by these primordial BHs can be registered in the near future, while the neutrino flux may be still beyond observation. The significance of this model would be difficult to overestimate, because these BHs would present a unique link connecting early universe and particle physics.

After this paper was completed, we became aware of the paper [32] where a similar idea was explored. However, the authors of this work assumed much lighter BHs which is in contradiction with our results.

Acknowledgments

C.B. and A.A.P. are supported in part by NSF under grant PHY-0547794 and by DOE under contract DE-FG02-96ER41005.

-
- [1] W.N. Johnson, F.R. Harnden and R.C. Haymes, *Astrophys. J.* **172**, L1 (1972);
M. Leventhal, C.J. MacCallum and P.D. Stang, *Astrophys. J.* **225**, L11 (1978).
- [2] W.R. Purcell *et al.*, *Astrophys. J.* **491**, 725 (1997);
P.A. Milne, J.D. Kurfess, R.L. Kinzer and M.D. Leising, *New Astron. Rev.* **46**, 553 (2002) [arXiv:astro-ph/0110442].
- [3] J. Knodlseder *et al.*, *Astron. Astrophys.* **441**, 513 (2005) [arXiv:astro-ph/0506026].
- [4] P. Jean *et al.*, *Astron. Astrophys.* **445**, 579 (2006) [arXiv:astro-ph/0509298];
G. Weidenspointner *et al.*, *Astron. Astrophys.* **450**, 1013 (2006) [arXiv:astro-ph/0601673].
- [5] G. Weidenspointner *et al.*, arXiv:astro-ph/0702621.
- [6] J.F. Beacom and H. Yüksel, *Phys. Rev. Lett.* **97**, 171301 (2005) [arXiv:astro-ph/0512411].
- [7] P.A. Milne, L.S. The and M.D. Leising, *Astrophys. J. Suppl.* **124**, 503 (1999) [arXiv:astro-ph/9901206];
P.A. Milne, M.D. Leising and L.S. The, arXiv:astro-ph/9911517.
- [8] N. Guessoum, P. Jean and N. Prantzos, *Astron. Astrophys.* **457**, 753 (2006) [arXiv:astro-ph/0607296].
- [9] T. Totani, *Publ. Astron. Soc. Jap.* **58**, 965 (2006) [arXiv:astro-ph/0607414].
- [10] L. Titarchuk and P. Chardonnet, *Astrophys. J.* **641**, 293 (2006) [arXiv:astro-ph/0511333].
- [11] C. Boehm, D. Hooper, J. Silk, M. Casse and J. Paul, *Phys. Rev. Lett.* **92**, 101301 (2004) [arXiv:astro-ph/0309686];
D. Hooper, F. Ferrer, C. Boehm, J. Silk, J. Paul, N.W. Evans and M. Casse, *Phys. Rev. Lett.* **93**, 161302 (2004) [arXiv:astro-ph/0311150];
C. Boehm and P. Fayet, *Nucl. Phys. B* **683**, 219 (2004) [arXiv:hep-ph/0305261].
- [12] C. Picciotto and M. Pospelov, *Phys. Lett. B* **605**, 15 (2005) [arXiv:hep-ph/0402178].
- [13] J.M. Frere, F.S. Ling, L. Lopez Honorez, E. Nezri, Q. Swillens and G. Vertongen, *Phys. Rev. D* **75**, 085017 (2007) [arXiv:hep-ph/0610240].
- [14] D.H. Oaknin and A.R. Zhitnitsky, *Phys. Rev. Lett.* **94**, 101301 (2005) [arXiv:hep-ph/0406146].
- [15] C. Bambi and A.D. Dolgov, *Nucl. Phys. B* **784**, 132 (2007) [arXiv:astro-ph/0702350].
- [16] J.H. Huh, J.E. Kim, J.C. Park and S.C. Park, arXiv:0711.3528 [astro-ph].
- [17] N. Prantzos, *New Astron. Rev.* **50**, 553 (2006).
- [18] J.C. Higdon, R.E. Lingenfelter and R.E. Rothschild, arXiv:0711.3008 [astro-ph].
- [19] Y. Ascasibar, P. Jean, C. Boehm and J. Knodlseder, *Mon. Not. Roy. Astron. Soc.* **368**, 1695 (2006) [arXiv:astro-ph/0507142];
P. Fayet, D. Hooper and G. Sigl, *Phys. Rev. Lett.* **96**, 211302 (2006) [arXiv:hep-ph/0602169].
- [20] P.N. Okeke and M.J. Rees, *Astron. Astrophys.* **81**, 263 (1980); P.N. Okeke, *Astrophys. Space Sc.* **71**, 371 (1980).
- [21] J.H. MacGibbon and B.J. Carr, *Astrophys. J.* **371**, 447 (1991).
- [22] A. Dolgov and J. Silk, *Phys. Rev. D* **47**, 4244 (1993).
- [23] S.W. Hawking, *Comm. Math. Phys.* **43**, 199 (1975).
- [24] B.J. Carr, *Lect. Notes Phys.* **631**, 301 (2003) [arXiv:astro-ph/0310838];
B.J. Carr, in *Proceedings of 59th Yamada Conference on Inflating Horizon of Particle Astrophysics and Cosmology*, Tokyo, Japan, 20-24 Jun 2005 [arXiv:astro-ph/0511743].
- [25] D.N. Page, *Phys. Rev. D* **13**, 198 (1976).
- [26] J.H. MacGibbon and B.R. Webber, *Phys. Rev. D* **41**, 3052 (1990).
- [27] R.L. Kinzer, W.R. Purcell and J.D. Kurfess, *Astrophys. J.* **515**, 215 (1999);
L. Bouchet *et al.*, *Astrophys. J.* **635**, 1103 (2005) [arXiv:astro-ph/0510084].
- [28] R. Schaeffer, D. Méra and G. Chabrier, *Acta Physica Pol. B* **29**, 1905 (1998).
- [29] J.F. Navarro, C.S. Frenk and S.D.M. White, *Astrophys. J.* **462**, 563 (1996) [arXiv:astro-ph/9508025].
- [30] P. Ullio, L. Bergstrom, J. Edsjo and C. Lacey, *Phys. Rev. D* **66**, 123502 (2002) [arXiv:astro-ph/0207125].
- [31] G.D. Kribs and I.Z. Rothstein, *Phys. Rev. D* **55**, 4435 (1997) [Erratum-ibid. *D* **56**, 1822 (1997)] [arXiv:hep-ph/9610468].
- [32] P.H. Frampton and T.W. Kephart, *Mod. Phys. Lett. A* **20**, 1573 (2005) [arXiv:hep-ph/0503267].
- [33] The first evidences of the Galactic 511 keV line date back to the '70s [1]. Over the past 40 years, there have been numerous publications on the observation of this line, see e.g. [2] and references therein for more recent measurements.
- [34] Throughout the paper we use $\hbar = c = k_B = 1$ units.
- [35] For $M \gg 10^{17}$ g, neutrinos, photons and gravitons are assumed massless and all the other particles are neglected. For $5 \cdot 10^{14} \ll M \ll 10^{17}$ g, electrons and positrons can also be considered massless. The apparent discrepancy with ref. [25] is just due to the inclusion of τ neutrinos. The extension of the flux and power factors to include τ neutrinos is given in ref. [26].
- [36] This is due to the fact that neutrino flux receives contributions from all three light neutrino generations and that the emission rate for spin-1/2 particles is higher than the emission rate for spin-1 ones [25].
- [37] If the density contrast appeared as a result of the QCD phase transition, then the masses of the BHs created according to the mechanism of ref. [22] would be cut-off from below by the mass inside the horizon at this moment, namely by approximately the solar mass. But the mechanism allows for generation of large density perturbations at much earlier stage, e.g. at $T = 10^8 - 10^9$ GeV. In this case the mass inside the horizon could be as small as $10^{16} - 10^{14}$ g.

Erratum

We overestimated the total annihilation rate in the Galaxy almost by factor 2. Instead of the value

$$3 \cdot 10^{43} \text{ s}^{-1}, \quad (16)$$

used in the paper, the correct one is

$$1.6 \cdot 10^{43} \text{ s}^{-1}. \quad (17)$$

Our error was based on the statement of ref. [6] of our paper where it is written that “the true annihilation rate is 3.6 times larger than would be deduced from the 0.511 MeV flux alone”. The corrected number of the annihilation rate results in shift down of the theoretical curves in figs. 1 and 5 by factor 1.8 – 1.9. We thank Pierre Jean for indicating to this error.